

Continuation Progress Report

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Title: Nuclear and Particle Physics Research at the University of Richmond

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Annual Reporting Period

1 Introduction

In this report we describe the progress made during the period January 1, 2016 to December 31, 2016 under contract number DE-FG02-96ER40980 entitled *Nuclear and Particle Physics at the University of Richmond*, Gerard P Gilfoyle (PI).¹ See pages 6-7 for a summary. The research is part of the electromagnetic nuclear physics program in Hall B at the Thomas Jefferson National Accelerator Facility (JLab) which houses the new CLAS12 detector nearing the end of construction. In 2016 the group included one faculty member (Gilfoyle), three undergraduates at the University of Richmond (a primarily undergraduate institution), and a masters student from the University of Surrey in the UK. One of these undergraduates, Keegan Sherman, has applied to Ph.D. programs and wants to pursue his doctorate in nuclear physics. Gilfoyle mentored a masters student Surrey through a joint Surrey/Richmond program. In June 2015, Gilfoyle was elected chair of the CLAS Collaboration for a two-year term that will include first beams in the new CLAS12 detector at JLab. He received release time from the University in the 2016-2017 academic year to support his work as CLAS chair. In this Introduction we outline the Richmond physics program, list recent accomplishments, and discuss the budget. More details on the physics projects and service work are below.

The Richmond group is currently working on analysis projects described below and software for the simulation, reconstruction, and analysis of data from the new CLAS12 detector in Hall B upon completion of the 12 GeV Upgrade.² Gilfoyle is spokesperson and contact person on an experiment to measure the neutron magnetic form factor G_M^n in Hall B entitled *Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium* (JLab experiment E12-07-104). The experiment builds on our experience with the previous detector in Hall B and will run in the first five years after the Upgrade is complete [1, 2, 3]. It received a scientific rating of A⁻ by PAC35 in 2010 and 30 days of beamtime [4, 5]. Gilfoyle is co-spokesperson on another 12-GeV proposal to measure G_M^n in Hall A entitled *Precision Measurement of the Neutron Magnetic Form Factor Up to $Q^2 = 18.0 (GeV/c)^2$ by the Ratio Method* (JLab experiment E12-09-014). He is also co-spokesperson on a 12-GeV proposal entitled *Quark Propagation and Hadron Formation* (JLab experiment E12-06-117) [6, 7]. Current physics projects focus on preparations for E12-07-104 and completion of CLAS12. In the last year we have developed software to provide the corrected geometry information for the Silicon Vertex Tracker (SVT) to the CLAS12 simulation (*gemc*) and to the reconstruction code. We have also written algorithms to perform track-based alignment of the CLAS12 detector and to reconstruct events in the CLAS12 time-of-flight systems. Gilfoyle continues work on analysis of existing CLAS6 data (CLAS6 is the previous detector that occupied Hall B before the 12 GeV Upgrade). He is spokesperson on a CLAS6 Approved Analysis *Out-of-Plane Measurements of Deuteron Structure Functions* to extract the fifth structure function of the deuteron [8].³ A draft analysis note has been submitted to an internal Collaboration review.

During the period of this report Gilfoyle was co-author on five refereed articles [9, 10, 11, 12, 13] and was invited to give a talk entitled *Future Measurements of the Neutron Magnetic Form Factor at Jefferson Lab* at the European Center for Theoretical Studies in Nuclear Physics and Related areas in Trento, Italy [14]. Last summer three undergraduates, Keegan Sherman, Alexander Balsamo, and David Brakman, worked with Gilfoyle at Richmond and JLab. Mr. Brakman worked closely with Chris Cuevas (one of the JLab engineering staff) on-site at JLab. Two of these undergraduates were supported by the DOE grant and one was supported by other University of Richmond funds. All three presented their work at the Fall, 2016 meeting of the Division of Nuclear Physics (DNP) of the APS [15, 16, 17]. Peter Davies was the masters student in the group from Surrey. He also presented his work in a poster at the DNP meeting [18].

We anticipate that at the end of the current budget period (May 31, 2017) there will be less than 10% of the budget period funding remaining in the grant.

2 Physics Projects

We have developed software to generate the ideal geometry information for the Silicon Vertex Tracker (SVT) and to correct for misalignments created during manufacture. The SVT is a silicon strip detector consisting of 132, flat silicon modules each with 256 strips that form a barrel near to and around the CLAS12 target location. To reach its design goals we need to know the geometry within a few microns. To test the SVT geometry we started

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²The JLab accelerator energy has been doubled 12 GeV and a new detector in Hall B is under construction, CLAS12.

³A CLAS Collaboration member can write a proposal to analyze existing, 6-GeV CLAS (CLAS6) data which is reviewed by a committee of Collaboration members, and defended before the Collaboration who then vote to approve it.

by comparing the engineering drawings of the SVT, calculations of the ideal geometry from a minimal set of parameters, and the actual values used in the CLAS12, physics-based simulation *gemc* and in the reconstruction code that reads in that simulated data. We found discrepancies as large as a few hundred microns. We reconciled the differences between these different sources of the geometry down to a maximum of about two microns and usually much less. We also developed the code and parameters so the simulation and reconstruction programs now construct the geometry from the same source. We also developed tools to correct the SVT geometry for misalignments between the ideal geometry and the actual positions in the SVT.

In parallel with the SVT geometry project we have also written code using the program *millepede* to measure the misalignments of the SVT. [19] The *millepede* code uses a least squares approach to simultaneously fit straight lines to cosmic-ray tracks and shifts in the geometry. We found the important misalignments were ones parallel to the silicon module face and transverse to the beam direction. Our use of *millepede* was first validated using simulated cosmic rays in *gemc* and then applied to a cosmic-ray sample collected in May, 2016. Our results are shown in the figure. These results are for a sample of Type 1 events which are cosmic rays that are nearly vertical and pass through the center of the SVT triggering all sixteen horizontal modules in this region of the detector. These events are easier to understand and interpret than shallow-angle particles coming from the sides. They are also more abundant. The vertical axis is the vertical position of each silicon module with the origin at the SVT center (also where the target will be located). The horizontal axis is the centroid of the residual between the measured, horizontal position of the track on the face of each silicon module and the straight-line fit. The uncertainties represent the width of the residual distribution (not the uncertainty on the position of the centroid). This width is more closely related to the resolution of the SVT. The blue points show the residuals we extracted with the ideal geometry applied to the real, cosmic ray data. Ideally, the residuals should cluster close to zero with an uncertainty of about twenty microns. Misalignments are apparent - some in the hundreds of microns. These data were analyzed and fit to straight line tracks using *millepede* to extract the shifts in the geometry that would minimize these residuals. These shifts were then applied to the SVT geometry in the reconstruction code and the data re-analyzed. The corrected residuals are shown in the red points. They all lie close to zero with a standard deviation of about 20-30 microns which is close to the expected uncertainty. Our results are described in Peter Davies (Surrey masters student) thesis which is in preparation and will be the subject of a future CLAS12-NOTE.

We also worked with the team developing the analysis code for the time-of-flight (TOF) systems in CLAS12. The project builds on Gilfoyle's experience in 2013 when he mentored another Surrey masters student who wrote the first version of the program [20]. There are two of these systems, one in the Forward Detector which consists of large flat panels of scintillators. Some of the panels (1a and 1b) are arranged one behind the other so particles typically strike scintillators in both panels. There is also another TOF system in the Central Detector consisting of a single layer of scintillators arranged in a cylinder around the target. Gilfoyle managed the bi-weekly meetings of the TOF software group for most of 2016. The focus was on reconstructing the position and signal size of the scintillator hits and, for the Forward TOF, combine the signals from panels 1a and 1b. Panel 1a sits in front of panel 1b. We explored algorithms for combining the signals from the two panels to obtain better resolution than we could obtain with either panel alone. We found combining the results for the panels and correcting for the propagation of tracks from one panel to the next yielded a significant improvement in the timing resolution. For example, the standalone electron timing resolution was 149 ps and 61 ps for panels 1a and 1b, respectively. The resolution of the combined panels improved to 48 ps. Gilfoyle gave the progress report at the spring CLAS Collaboration meeting [21]. Our results will be described in a future CLAS12-NOTE.

We continued our preparations for the G_M^n measurement (Experiment E12-07-104). In that experiment we will measure the neutron detection efficiency (NDE) using the reaction ${}^1\text{H}(e, e'\pi^-n)$ as a source of tagged neutrons. We detect the scattered electron and π^+ , predict the location of the neutron in CLAS12, and then

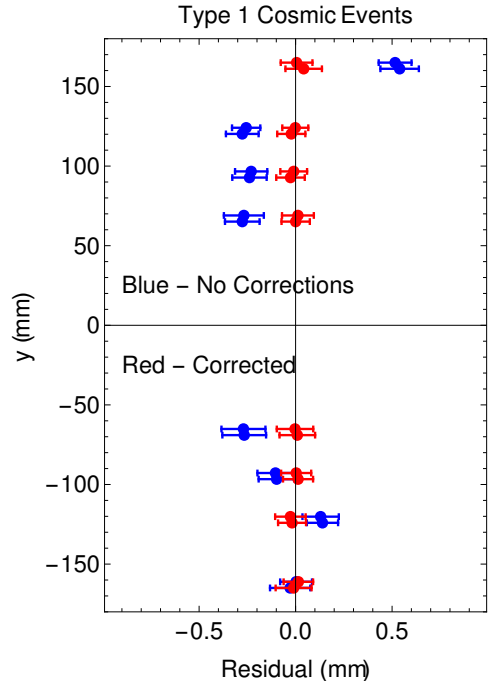


Figure 1: Cosmic-ray residuals in the CLAS12 silicon vertex tracker (SVT) for Type 1 events before (blue) and after (red) correcting for misalignments using *millepede*.

search for that neutron. The NDE is the ratio of the detected neutrons to the ones expected to strike the fiducial volume of CLAS12. One of the Richmond undergraduates (Sherman) ported the JLab version of the Pythia code to our computing cluster at Richmond [22]. This program generates events for the inelastic reactions we will use to measure the NDE. Those events were simulated in *gemc* and the algorithm for extracting NDE applied. This last algorithm was written as a groovy script using the current version of the CLAS12 reconstruction software [23]. We found the NDE was about 50% in the electromagnetic calorimeter - comparable to our results with CLAS6 [1]. Mr. Sherman presented his work in a poster at the fall, 2016 DNP meeting [15].

In the G_M^n measurement we extract this observable from the ratio of e-n to e-p quasi-elastic scattering on deuterium. Another Richmond undergraduate (Balsamo) began development of the groovy scripts to perform this analysis also using the latest version of the CLAS12 reconstruction code. To select quasi-elastic proton and neutron events in an unbiased way we use a single cut for both particles on θ_{pq} , the angle between the detected nucleon direction and the predicted one using the scattered electron information. Mr. Balsamo also presented his work at the fall, DNP meeting [17].

One of my Richmond students (Brakman) was funded by the DOE grant and he worked in the electronics group at JLab during summer, 2016. He developed and tested an algorithm to generate a uniform circular beam raster pattern for the FROST polarized target. He used LabView to control proxy hardware components and wrote the controls code to produce the raster pattern. Mr. Brakman also presented his work at the fall, 2016 DNP meeting [16].

Gilfoyle continues to work on the analysis of the structure function in the ${}^2\text{H}(\vec{e}, e'p)n$ reaction which is under CLAS Collaboration review. Progress was moderate during the year because of Gilfoyle commitment to the CLAS12 development projects and his duties as CLAS Collaboration chair.

3 Professional and CLAS Collaboration Service Work

Gilfoyle was elected chairperson of the CLAS Coordinating Committee (CCC) of the CLAS Collaboration in June 2015 and began his two-year term September 1, 2015. The CCC is the main governing body of the Collaboration. The Collaboration consists of about 220 physicists from 39 institutions in twelve countries and is responsible for the construction, commissioning, and operation of the CLAS12 detector. The Chairperson of the CCC is the Collaboration spokesperson and principal contact to the Jefferson Lab directorate for the CLAS Collaboration. The chairperson has responsibility for assuring smooth operation of the Collaboration and organizing the three annual Collaboration meetings [24].

The last year has been a busy one for the CLAS Collaboration with first beam in CLAS12 expected in February, 2017 followed by an engineering run and first production run in fall, 2017. In anticipation of the first experiment, we organized three CLAS12 Workshops in 2016 in conjunction with our regular CLAS Collaboration meetings. Each workshop consisted of a full day of status reports of the different detector subsystems, software progress, and planning discussions. Attendance at each of the meetings was high.

Planning for the Collaboration's transition to CLAS12 operations was also part of the regular, three-day Collaboration meetings (we meet three times a year as required in the CLAS Charter). The topics included membership issues like the status of current members who were analyzing CLAS6 data, but not planning to work on CLAS12 experiments and discussions of shift policies for the 2017 runs. We have also encouraged our software team to move their code and documentation to the JLab gitHub area to provide an easy-to-find, modern resource for accessing the CLAS12 codes. The CLAS12 software effort was the focus of a study by an ad hoc committee on Common Tools. This group of Collaboration members provided a plan for the software effort with an eye to readiness for the 2017 runs and made recommendations on an organizational structure to guide that effort. We have now formed a team with broad experience with CLAS6 to monitor and advise the current software efforts for the different subsystems. In the near future we will create another team mostly from the spokespersons for the fall, 2017 run to begin reviewing the analysis plans in spring, 2017 so we are ready to analyze the first production data in a timely fashion.

The rest of the Collaboration business continued going forward. We held three Collaboration meetings with about seventy plenary talks presented. We saw progress on twelve ad hoc reviews of papers for publication and did internal reviews of twelve new beamtime proposals for PAC44. The Collaboration has three physics working groups and elections were held in all three groups to get the leadership team in place now before the arrival of the first data in 2017. Lastly, Gilfoyle led the effort to submit a beamtime scheduling request to the JLab management for Run Group B. The G_M^n experiment is part of this run group.

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- [13] C. A. Paterson et al. Photoproduction of Λ and Σ^0 hyperons using linearly polarized photons. *Phys. Rev.*, C93(6):065201, 2016.
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- [16] D. Brakman, C. Cuevas, and G.P. Gilfoyle. Uniformly Rastering an Electron Beam on a Polarized Cryotarget. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2016.
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Summary of Contract-Related Activities

Refereed Publications

1. I. Senderovich et al. First measurement of the helicity asymmetry E in η photoproduction on the proton. *Phys. Lett.*, B755:64–69, 2016.
2. X. Zheng et al. Measurement of Target and Double-spin Asymmetries for the $\vec{e}\vec{p} \rightarrow e\pi^+(n)$ Reaction in the Nucleon Resonance Region at Low Q^2 . *Phys. Rev.*, C94(4):045206, 2016.
3. R. Dickson et al. Photoproduction of the $f_1(1285)$ Meson. *Phys. Rev.*, C93(6):065202, 2016.
4. P. E. Bosted et al. Target and beam-target spin asymmetries in exclusive π^+ and π^- electroproduction with 1.6- to 5.7-GeV electrons. *Phys. Rev.*, C94(5):055201, 2016.
5. C. A. Paterson et al. Photoproduction of Λ and Σ^0 hyperons using linearly polarized photons. *Phys. Rev.*, C93(6):065201, 2016.

Invited Talks

1. G.P. Gilfoyle. Future Measurements of the Neutron Magnetic Form Factor at Jefferson Lab. Presented at Probing Transverse Nucleon Structure at High Momentum Transfer, Trento, Italy, April 21, 2016, 2016.

Contributed talks and posters.

1. G.P. Gilfoyle. CLAS Collaboration Transition to CLAS12 Operations. CLAS Collaboration Meeting, November 2, 2016.
2. K. Sherman and G.P. Gilfoyle. Measuring the Neutron Detection Efficiency in CLAS12. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2016.
3. D. Brakman, C. Cuevas, and G.P. Gilfoyle. Uniformly Rastering an Electron Beam on a Polarized Cryotarget. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2016.
4. Balsamo A. and G.P. Gilfoyle. Measuring Quasi-Elastic e-n and e-p Scattering from Deuterium. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2016.
5. Davies P. and G.P. Gilfoyle. Geometry Calibration of the SVT in the CLAS12 Detector. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2016.
6. G.P. Gilfoyle *et al.* Time of Flight Software Status. CLAS12 Workshop, February 23, 2016.

Other Presentations

G.P. Gilfoyle. Hunting for Quarks and Gluons. University of Richmond Physics Seminar, August 24, 2016.

Service Work

1. Chair, CLAS Collaboration, elected June, 2015, term began September 1, 2015.
2. Review, Physical Review Letters
3. Reviewer, CLAS Collaboration.
4. Review, US Department of Energy, Office of Science, Nuclear Physics Program.